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A POSSIBLE EXPLANATION OF THE MECHANISM OF FORMATION OF THE EQUATORIAL JET ON THE SURFACE OF JUPITER

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16. Abstract

Formation of the equatorial jet on the Jovian surface is explained as a consequence of the Taylor-Proudman theorem and the asymptotic theory of motion of low-viscosity fluids in a rotating spherical shear layer. The model adopted suggests that the striated structure of the Jovian surface at latitudes from ± 10 to $\pm 45^{\circ}$ can be explained as the outflow at the external boundary of the atmosphere of convective cells having the shape of axisymmetric rolls extended along the axis of rotation in the meridional direction. Depth of the layer is found to be of the order of 1000 km.

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A POSSIBLE EXPLANATION OF THE MECHANISM OF FORMATION OF THE EQUATORIAL JET ON THE SURFACE OF JUPITER

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(Presented by Academician G. I. Petrov, November 3, 1976)

1. The proposed explanation of the mechanism of formation of the equatorial jet on the surface of Jupiter is based on a fact that is a direct consequence of the Taylor-Proudman theorem and that is known from the asymptotic theory of motion of low-viscosity fluids in a rotating spherical shear layer /1-3/. The similarity parameters of this motion include the Reynolds number $Re = \Omega_1 r_1^2/\nu$, the relative rate of rotation $\varepsilon = (\Omega_2 - \Omega_1)/\Omega_1$, and the relative thickness of the layer $\delta = (r_2 - r_1)/r_1$ (r_1, r_2, Ω_1, and Ω_2 are the radii and angular velocity of the internal and external boundaries of the spherical layer, and ν is the kinematic viscosity). We know /1-3/ that for large Reynolds numbers $Re \gg 1$ and small $\varepsilon \ll 1$, in the liquid is formed a cylindrical shear layer with radius R, equal to the radius of the internal boundary r_1 separating the fluid rotating as a solid at angular velocity Ω_2 outside the cylinder $R > r_1$ from the stream inside the cylinder. /60*

* Numbers in the margin indicate pagination in the foreign text.

Inside the internal region $R < r_1$, everywhere--except for the boundary layers--the angular rate of rotation ω and the stream function ψ of the meridional stream depend only on the distance R from the axis of rotation. The angular rate of rotation changes from Ω_1 to Ω_2; the meridional stream represents motion from the slowly rotating boundary to the more rapidly rotating boundary along the cylindrical surfaces with generatrices parallel to the axis of rotation. All the backflow of the fluid takes place in the thin cylindrical shear layer near the cylinder with radius $R = r_1$. Both the angular and the meridional stream velocities change sharply in the shear layer, which is wholly within the spherical layer and does not extend beyond the boundaries.

When we look at planetary atmospheres, the role of the upper boundary can be played by the zonal geostrophic stream caused by solar radiation in the upper thin cloud layer of the atmosphere [4].

As shown in [5], temperature stratification in the upper cloud layer is stable down to depths of 20-50 km. Below this it appears that there is a region of turbulent convection, where the coefficient of effective viscosity η must be much larger than in the upper layer. Then the effect of the upper layer on the lower can be depicted as tangential stresses $\tau_{r\phi}(\vartheta)$ (r, ϑ, ϕ are spherical coordinates). The dynamic condition for specifying τ, in contrast to the Proudman-Stewartson kinematic condition [2, 3], lets us extend the cylindrical shear layer to the external boundary and allow it to suffer a discontinuity in the angular rate of rotation at the external boundary.

2. To confirm this fact, numerical calculations were made /6 of the nonlinear boundary value problem for Navier-Stokes equations under the following boundary conditions written in dimensionless form:

$$r=1: \quad \psi=\frac{\partial\psi}{\partial r}=0, \quad w=\sin\vartheta;$$

$$r=1+\delta: \quad \psi=\frac{\partial^2\psi}{\partial r^2}-\frac{2}{r}\frac{\partial\psi}{\partial r}=0, \quad \frac{\partial w}{\partial r}-\frac{w}{r}=\tau\sin\vartheta;$$

$$\vartheta=0,\pi: \quad \psi=w=0 \quad (w=\omega r\sin\vartheta).$$

Appearing instead of ε in this case is the dimensionless tangential stress $\tau = \tau_0/(\rho\eta\Omega_1)$ (Ω_1 is the angular rate of rotation of the internal sphere, ρ is the density of the medium, and τ_0 is the tangential stress at the equator).

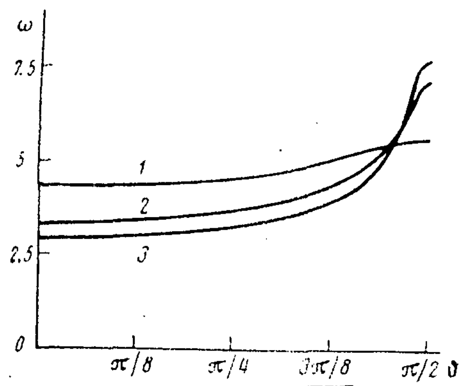


Fig. 1. Distribution of angular velocity ω at the external boundary when $\tau = 160$ and $\delta = 0.025$:
1. Re = 2000 2. Re = 5000
3. Re = 7500

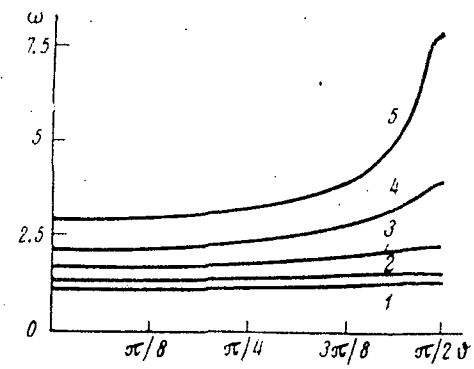


Fig. 2. Distribution of angular velocity ω at the external boundary when Re = 7500 and $\delta = 0.025$:
1. $\tau = 10$ 2. $\tau = 30$
3. $\tau = 40$ 4. $\tau = 80$
5. $\tau = 160$

The system of equations was solved by the method of finite differences using a procedure described in [6], for different values of the determining parameters. Some results of the calculations are shown in Figs. 1-3. In all these cases the flow pattern near the equator was symmetrical. Calculations were also made for flows of the fluid layer, in which the density and the

dynamic viscosity underwent a discontinuity equal to $\rho_1/\rho_2 = \mu_1/\mu_2 = k$ in the middle of the layer when $r = r_1 + \delta/2$ (the subscripts 1 and 2 here refer to the internal and external parts of the layer, respectively).

The conclusions following can be drawn on the basis of calculations:

1) for large Re numbers, just as in the Proudman-Stewartson problem, there is a tendency for a cylindrical drifting layer to form near the cylinder with radius r_1; however, in contrast to the first problem, this shear layer extends to the external boundary of the spherical layer, which shows up in an abrupt change in the angular velocity at the surface near $\vartheta = \arcsin(r_1/r_2)$ (Figs. 1-3), that is, the phenomenon of significant equatorial acceleration is disclosed.

2) an increase in the Re number, given constant δ and τ leads to thinner boundary layers (Fig. 1);

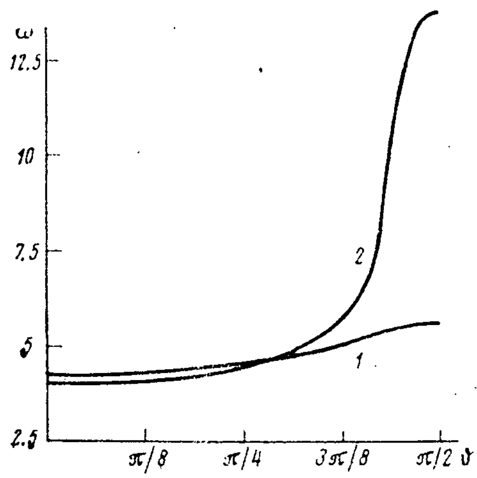
3) τ determines the amplitude of the discontinuity in the azimuthal velocity in the shear layer for large fixed Re (Fig. 2);

4) the smaller the δ and τ, the larger must be the Re num- /62
ber in forming the shear layer (Figs. 1 and 3);

5) the internal boundary r_1 is not necessarily a solid surface, but can be the interface of fluids differing in density.

3. Possibly, motions similar to the motions described above --for specific values of the similarity parameters Re, τ, and δ-- can serve as a gross model in explaining that, on large planets and, in particular, on Jupiter, there is an equatorial jet with well-defined boundaries. We know [8] that clouds forming the visible surface of Jupiter have a striated structure and rotate as two different systems: clouds in the limits $\pm 10^{\circ}$ from the equator have a mean period of rotation $9^h 50^m 30^s$ and the extra-equatorial zone rotates with the period $9^h 55^m 40^s.6$. Thus, on

the Jovian surface there is observed an equatorial jet that has a relative velocity of the order of 100 m/sec and very sharply defined boundaries (Fig. 4).



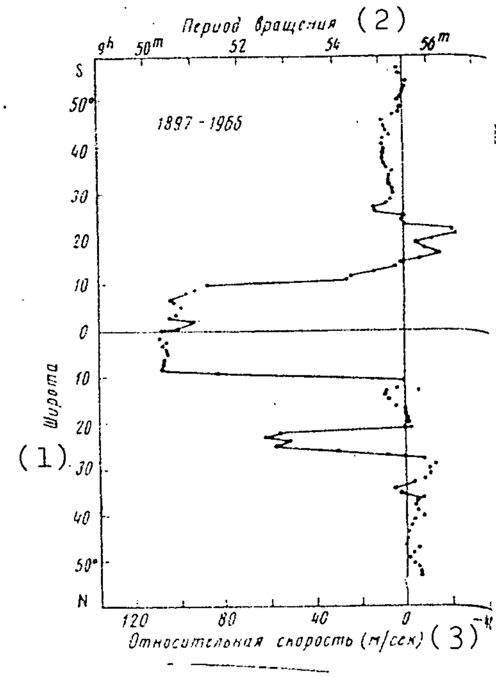


Fig. 3. Distribution of angular velocity ω at the external boundary when Re = 2000 and τ = 160:
1. τ = 0.025 2. τ = 0.05

Fig. 4. Mean relative rate of rotation of Jovian surface as a function of zenographic latitude from the data in /‾8_7
KEY: 1. Latitude
2. Period of rotation
3. Relative velocity (m/sec)

If the proposed model is valid and if the well-defined boundary of the Jovian equatorial jet is an outflow onto the surface of the Stewartson shear layer, from the observational data we can obtain some estimates for the dimensionless parameters of

the problem. From the width of the equatorial jet, located approximately between $\phi = \pm 10^{\circ}$ latitude, we can readily find the depth of the atmosphere and, therefore, the parameter δ. In fact, $r_1 = r_2 \cos \phi_0$ (here r_2 is the visible radius of Jupiter, equal to approximately $7 \cdot 10^9$ and identified with the upper boundary of the spherical layer, and r_1 is not necessarily the solid boundary of the planet, but--possibly--the interface of the material or layer with a large density gradient, and ϕ_0 is the width of the boundary of the equatorial jet), from which $\delta = (1 = \cos \phi_0)/$ $/\cos \phi_0 \sim 0.015$, that is, the depth of the layer proves to be of the order of 1000 km, which coincides with the upper boundary of the atmospheric depth, based on Peebles' estimates [9]. It must be kept in mind that all estimates have a highly approximately /63
character, since in the real atmosphere the gas is highly stratified and compressible, while the theoretical calculations were made for a homogeneous incompressible fluid. So in the following treatment we will use the means of the parameters of the medium, labelling them with the subscript s.

The thickness of the equatorial jet boundary is of the order of 1-2°, that is, $\Delta R \approx 200\text{-}400$ km and $\Delta = \Delta R / r_1 \approx 0.003\text{-}0.006$. If we know the relative velocity of the equatorial jet, we can find the dimensionless parameter $\varepsilon = \Delta\Omega/\Omega \approx 0.0084$ and the dimensionless tangential stress in the cylindrical shear layer when $\tau = \tau_0/(\rho_s \eta \Omega) \approx \Delta\varepsilon/\Delta = 1\text{-}3$.

Now we present some energy estimates. The total influx of solar energy into the Jovian atmosphere [10] $Q \approx 10^{25}$ erg/sec. If we assume that a large part of this energy is transformed into the kinetic energy of motion $E \sim (0.1\text{-}0.01)Q$, which then is dissipated by the effective turbulent viscosity, chiefly in the shear layer, then we can estimate the coefficient of this viscosity in the planetary atmosphere η. Dissipation of the energy in the cylindrical shear layer can be estimated as follows:

$$E \sim \eta\rho_s (\Delta w/\Delta R)_s^2 \cdot 2\pi r_1^2 \sin\varphi_0 \Delta R.$$

Assuming $\Delta w \approx 100$ m/sec, $\rho_s \approx 10^{-2}$ g/cm^3, and $r_1 \approx 7 \cdot 10^9$ cm, we find the coefficient of turbulent viscosity $\eta \approx 10^5$-10^6 cm^2/sec. The Reynolds number corresponding to the large-scale motions in the Jovian atmosphere here turns out to be of the order of 10^{10}-10^{11}. The values of η agree with estimates of effective viscosity given in /11/ and are somewhat smaller than the values in /12/.

Numerical calculations, given values of the similarity parameters corresponding to the estimates obtained above for Jupiter, do not now appear realistic, therefore we are limited only to qualitative conclusions. Qualitative analysis shows us that for the values $Re \approx 10^{10}$, $\delta \approx 0.015$, and $\tau \approx 1$-3 we must expect that the cylindrical shear layer will be quite thin and its outflow at the upper boundary will cause an abrupt change in the rate of rotation of the planetary surface. Within the scope of this model, the striated structure of the Jovian surface at latitudes from ± 10 to $\pm 45^\circ$ can be attributed to the outflow at the external boundary of convective cells having the shape of axisymmetric rolls extended along the axis of rotation in the meridional section. This shape of the cells, according to the Taylor-Proudman theorem, can originate when there is rapid rotation /13/ and the presence of shearing in the convective flow /14/.

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REFERENCES

1. Greenspan, H. P., Theory of Rotating Fluids, Cambridge, 1968.
2. Proudman, J., J. Fluid Mech. 1/5, (1956).
3. Stewartson, K., ibid. 26/1, (1966).
4. Khaltiner, Dzh., and Martin, F., Dinamicheskaya i fizicheskaya meteorologiya /Dynamic and Physical Meteorology/, Moscow, 1960.
5. Traffton, L. M., and Munch, G., J. Atmosph. Sci. 26/5, Part 1 (1969).
6. Simuni, L. M., Zhurn. prikl. mekh. i tekhn. fiz., No 6, (1965).
7. Chudov, L. A., and Kuskova, T. V., in: Chislennyye metody v gazovoy dinamike /Numerical Methods in Gas Dynamics/, Moscow, Moscow State University Press, 1963.
8. Chapman, C. R., J. Atmosph. Sci. 26/5, Part 1, (1969).
9. Peebles, P. J. E., Astrophys. J. 140/1, (1964).
10. Golitsyn, R. S., Vvedeniye v dinamiku planetnykh atmosfer /Introduction to the Dynamics of Planetary Atmospheres/, Leningrad, 1973.
11. Wallace, L., and Hunten, D. M., Astrophys. J. 182/3, (1973).
12. Shimizu, M., paper submitted to the 17th Meeting of COSPAR, San Paulo, Brazil, June, 1974.
13. Busse, F. H., J. Fluid Mech. 44/3, (1976).
14. Keller, B. S., and Yavorskaya, I. M., Aeromekhanika i gazovaya dinamika, sb. /Aeromechanics and Gas Dynamics, a collection of articles/, Moscow, Nauka Press, 1976.